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Removing Organic Contaminants from Groundwater
A Cost and Performance Evaluation

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16. ABSTRACT

More than 100 million Americans depend on groundwater as a source of drinking water. Three quarters of U.S. cities get their water supplies totally or in part from groundwater and one-third of the largest cities rely on groundwater for at least part of their potable water supply. A number of recent studies have documented the actual or potential contamination of our nation's groundwater on a wide scale. Some of this contamination is man made but much of it is of natural origin. In either case some form of treatment is required before contaminated groundwater can be used for water supply. USEPA's Drinking Water Research Division has been conducting bench, pilot and field studies on technologies that effectively treat groundwater. This paper reports some of the results from these studies.

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Removing organic contaminants from groundwater

A cost and performance evaluation

Robert M. Clark
Carol Ann Fronk
Benjamin W. Lykins, Jr.
U.S. Environmental Protection Agency
Cincinnati, OH 45268

Results of a number of recent studies show that much of our nation's groundwater currently is or soon will become contaminated. A survey conducted by EPA has documented that 22% of approximately 466 randomly sampled utilities that use groundwater as their source have produced drinking water that contains volatile organic chemicals (VOCs) at detectable levels (*1*).

In a given well, one or two compounds will predominate at relatively high concentrations, and several other compounds will be present at much lower concentrations (*2*). An affected supply typically contains several VOCs; trichloroethylene is detected most frequently and in highest concentration.

During the last eight years, the Suffolk County Health Department (Riverhead, NY) has examined the groundwater underlying Long Island for agricultural organic constituents and their decay products (*3*). In another study by the California Department of Food and Agriculture in 1983, dibromochloropropane, ethylene dibromide, and simazine were found in San Joaquin Valley wells (*3*). A report submitted to the California State Water Resources Board states that more than 2000 wells statewide have been found to be contaminated with dibromochloropropane (*4*).

In recognition of this growing problem, EPA has proposed maximum contaminant levels for VOCs that frequently are found in the groundwater used to supply drinking water (*5*). In addition, EPA is planning to propose maximum contaminant levels for 26 synthetic organic chemical contaminants that also are frequently found in groundwater (*6*).

In developing maximum contaminant levels, EPA is required by the Safe Drinking Water Act to demonstrate the feasibility of a technology for removing a contaminant. The Drinking Water Research Division (DWRD) of EPA is responsible for evaluating these technologies. The standard research protocol followed by DWRD is to evaluate unit processes at the bench level; test the process at the pilot scale; and, if its performance is promising, build a prototype for field evaluation. At all stages, cost and performance are key factors in moving a technology to the next phase. Thus when a technology is tested on a field scale, cost and performance data are routinely collected.

The various technologies being examined are discussed in this section, and a brief performance comparison is presented based on results to date. Table I summarizes the treatment technologies that DWRD is evaluating for removal of VOCs and synthetic organic chemicals (SOCs) from water supplies.

Field-tested technologies

Carbon adsorption. Extensive studies have been conducted on the use of granular activated carbon (GAC) treatment with the on-site regeneration of GAC. In the past, research has been devoted to demonstrating the effectiveness of GAC for surface water treatment (*7*). More recently, DWRD has been studying carbon treatment for removing VOCs and SOCs from groundwater in Suffolk County, NY, San Joaquin Valley, CA, and Wausau, WI. Each of these projects is designed to examine a different aspect of treatment with GAC and, except for Wausau, are intended to deal with the little-understood problem of pesticide contamination.

The groundwater in Wausau contains multiple contaminants that come from a nearby Superfund site and show a total organic carbon level of 7.6 mg/L. Although part of the TOC no doubt is associated with specific and nonspecific man-made organic chemicals, a signifi-

TABLE 1
Treatment technologies for removing SOCs and VOCs

Technology status	Technology description	Contaminants for which technology is best suited
Field-tested technologies	Carbon adsorption	VOCs and SOCs
	Packed-tower and diffused-air aeration	VOCs
Promising technologies	Conventional treatment	SOCs
	Ozone oxidation	VOCs and SOCs
	Reverse osmosis	VOCs and SOCs
	Ultraviolet treatment	VOCs and SOCs
	Ultrafiltration	Trihalomethane formation potential

cant portion may be associated with naturally occurring organics.

Although GAC is the principal removal technology being studied, air stripping was examined as a companion technology. The Wausau project was unique in that modeling techniques also were used to predict full-scale design criteria for a GAC plant (*8*). In addition to studying modeling, researchers also examined minicolumn technology, which allows investigators to acquire water from a given site and to study the performance of a small, high-pressure column in the presence of a natural water background. Results from these minicolumn experiments are expected to reproduce the breakthrough curves normally seen in pilot- and full-scale facilities.

Packed-tower aeration. Aeration technology has proved to be especially effective for the removal of VOCs. Moreover, the research in Wausau, which also incorporates air stripping and off-gas control technology, indicates that aeration may in some cases be cost effective for removing compounds that have somewhat lower Henry's law constants than normally would be expected to be effectively removed by this process. The off-gas control portion of the air-stripping project at Wausau was conducted in cooperation with the American Water Works Association Research Foundation in Denver.

DWRD is conducting another air-stripping research project in Baldwin Park, CA, to study the removal of VOCs from a groundwater supply. As in Wausau, the Baldwin Park project is examining the problems of off-gas control technology.

Another field-scale activity dealing with air stripping has been concluded in Brewster, NY. Modeling techniques and pilot-scale facilities were used to determine the scale-up relationships to be used for full-scale, air-stripping facilities. This project was designed to develop a technique that could be used by consulting engineers to predict the cost and performance of fullscale facilities using pilot aeration columns.

Promising technologies

Powdered activated carbon. Conventional treatment is unlikely to be used for removing organic contaminants from groundwater. Field studies, however, were conducted in Tiffin, OH, where the drinking-water source, the Sandusky River, contains high spikes of pesticides because of local seasonal applications of pesticides for agricultural purposes. Powdered activated carbon, added to water that normally receives only conventional treatment, was quite effective for removing SOCs.

Ozone oxidation. Ozone oxidation is being studied extensively in DWRD's in-house pilot-plant facilities. Controlled pilot-plant ozone treatment tests were conducted on 29 VOCs in distilled water and groundwater. Results showed that aromatic compounds, alkenes, and certain pesticides are removed well by ozone treatment, but that alkanes are removed poorly. Also, removal efficiency improves for the alkenes and aromatic compounds with increasing ozone dosage and for some alkanes with increasing pH. For most compounds, efficacy of ozone is not affected by the background water matrix. Groundwater and surface water used in ozone tests contain background TOC (distilled water does not), but this TOC does not affect the removal efficiency by ozone of the organics evaluated. Information from the literature concerning the ozone treatment of pure materials in the gaseous or liquid phase generally predicts the effectiveness of ozone in treating aqueous solutions.

Reverse osmosis. Reverse osmosis has shown some promise for removing both VOCs and SOCs from groundwater. Most of the efforts by DWRD to date have been conducted on a pilot or bench scale and have included some limited application of reverse osmosis for the removal of organics at the Suffolk County site. Initial indications are that certain reverse osmosis membranes are highly effective in removing a wide range of organic chemicals.

Ultraviolet treatment. Ultraviolet light also shows some promise for removing organic contaminants, particularly when it is combined with ozone. DWRD has funded a project with the Los Angeles Department of Water and Power that will remove VOCs from groundwater by using these two technologies. This project is designed to investigate the water-phase oxidation of VOCs and SOCs to CO_2 and water by using ozone in combination with UV light or with hydrogen peroxide. Gas-phase oxidation of VOCs by hydrogen peroxide, ozone, and UV light also appears promising and is being evaluated under an American Water Works Association Research Foundation contract. If the project succeeds, the need to deal with off-gas control problems will be eliminated.

Ultrafiltration. Studies have been conducted to evaluate the costs and performance of low-pressure membrane processes (ultrafiltration) for trihalomethane (THM) precursor reduction in small systems. A 150-day pilot-plant study of two aquifers that are highly contaminated with organic chemicals (both aquifers contained more than 400 μg/L THM after conventional treatment) produced a finished water that easily met the maximum contaminant level for THMs (100 μg/L). Costs appear to be reasonable (*9*). More extensive testing of this technology is underway at the University of Central Florida.

Secondary discharge problems

In evaluating treatment technology, one must be aware of the possibilities of creating secondary discharge problems. For example, during research on treating surface water supplies with GAC, it was discovered that dioxins were formed in the reactivation process. An extensive evaluation led to the installation of an afterburner, which was found to eliminate dioxin by-products when operated at a temperature of 1315 °C (2400 °F) (*10*). In Baldwin Park and in Wausau, gas-phase carbon adsorption was investigated for the removal of VOCs and SOCs from air-stripping waste gases.

Future work will concentrate on residuals control from various unit processes such as reverse osmosis and ultrafiltration. In addition, another technology, photooxidation, is not currently being examined, but is scheduled for future evaluation.

Performance comparisons

Table 2 summarizes the results of field and pilot testing for various technologies. The contaminants examined

TABLE 2
Performance summary for technologies examined

Organic compounds	Regulatory phase	Removal efficiency[a] GAC	Packed-tower aeration	Reverse osmosis	Ozone oxidation (2–6 ppm)	Conventional treatment
VOCs						
Alkanes						
Carbon tetrachloride	I	+ +	+ +	+ +	–	–
1,2-Dichloroethane	I	+ +	+ +	+	–	–
1,1,1-Trichloroethane	I	+ +	+ +	+ +	–	–
1,2-Dichloropropane	II	+ +	+ +	+ +	–	–
Ethylene dibromide	II	+ +	+ +	+	–	–
Dibromochloropropane	II	+ +	+	NA	–	–
Alkenes						
Vinyl chloride	I	+	+ +	NA	+ +	–
1,1-Dichloroethylene	I	+ +	+ +	NA	+ +	–
cis-1,2-Dichloroethylene	II	+ +	+ +	–	+ +	–
trans-1,2-Dichloroethylene	II	+ +	+ +	NA	+ +	–
Trichloroethylene	I	+ +	+ +	+	+	–
Aromatics						
Benzene	I	+ +	+ +	–	+ +	–
Toluene	II	+ +	+ +	NA	+ +	–
Xylenes	II	+ +	+ +	NA	+ +	–
Ethylbenzene	II	+ +	+ +	–	+ +	–
Chlorobenzene	II	+ +	+ +	+ +	+	–
o-Dichlorobenzene	II	+ +	+ +	+	+	–
p-Dichlorobenzene	I	+ +	+ +	NA	+	–
Styrene	II	+ +	+ +	NA	+ +	–
Pesticides						
Pentachlorophenol	II	+ +	–	NA	+ +	NA
2,4-D	II	+ +	–	NA	+	–
Alachlor	II	+ +	+ +	+ +	+ +	–
Aldicarb	II	NA	–	NA	NA	NA
Carbofuran	II	+ +	–	+ +	+ +	–
Lindane	II	+ +	–	NA	–	–
Toxaphene	II	+ +	+ +	NA	NA	–
Heptachlor	II	+ +	+ +	NA	+	NA
Chlordane	II	+ +	–	NA	NA	NA
2,4,5-TP	II	+ +	NA	NA	+	NA
Methoxychlor	II	+ +	NA	NA	NA	NA
Other						
Acrylamide	II	NA	–	NA	NA	NA
Epichlorohydrin	II	NA	–	NA	–	NA
PCBs	II	+ +	+ +	NA	NA	NA

[a] + + = Excellent (70–100%). Excellent removal category for carbon indicates that the compound has been demonstrated to be adsorbable onto GAC, either in full- or pilot-scale applications or in the laboratory. The data suggest that GAC can be a cost-effective technology.
+ = Average (30–69%)
– = Poor (0–29%)
NA = Data not available, or compound has not been tested by EPA Drinking Water Research Division.

have been catagorized as VOCs and pesticides. Three performance efficiencies have been defined: excellent (70–100%), average (30–69%), and poor (0–29%).

Table 2 was compiled from a variety of sources, including EPA–DWRD pilot- and field-scale studies, Henry's law constants for predicting the removal of some of the pesticides, and oxidative trends for predicting the removal of complex pesticides. Only a certain number of organic compounds can be evaluated; therefore, the removal, by oxidation, of other compounds with similar structures or within similar groups can be predicted from the organic compound evaluated. Although Table 2 provides only a general guideline for removal of compounds, several interesting trends can be determined from the data.

Cost and performance analysis

All of the field studies conducted by DWRD include cost and performance as part of the data gathered for later evaluation and extrapolation. In addition, as bench- and pilot-scale studies are conducted, cost estimates based on the development of equations and curves from previous studies are used to predict the most cost-effective technologies on which to concentrate.

This section will discuss and evaluate preliminary cost estimates for hypothetical groundwater contamination situations involving the six most commonly found volatile organic chemicals: trichloroethylene; tetrachloroethylene; 1,1,1-trichloroethane; *cis*-1,2-dichloroethylene, 1,2-dichloroethane; and 1,1-dichloroethylene. The performance characteristics of GAC, adsorption, tower aeration, and diffused air aeration used to remove volatile organics from groundwater will be considered.

GAC is an effective adsorbent that removes a broad spectrum of organics from drinking water. The performance of GAC can be summarized in terms of pounds of carbon/thousand gallons (10 m^3 water/m^3 carbon) of water re-

quired to reduce levels of selected volatile organics from a given influent concentration to a target effluent concentration. Air-to-water ratios required for using air stripping to remove VOCs from water can be calculated (*11*).

Treatment costs are included with the performance data (*12*). A treatment configuration is assumed, and costs are estimated to achieve a given level of removal for the VOCs considered. In this case, a groundwater source is assumed together with one of three technologies—aeration (including diffused-air aeration), towers, or GAC adsorption. The effluent stream from the treatment process is chlorinated, goes to a clear well, and then is distributed to a drinking-water system. In this analysis we will examine the cost tradeoffs among these technologies, assuming flows of 0.5 million gal/day or mgd (1896 m^3/day), 1 mgd (3785 m^3/day), and 10 mgd (3785 m^3/day), all operating at 70% capacity (*11*). Table 3 contains the relevant design assumptions. A cost comparison for removing this set of VOCs has been compiled (*11*).

Figure 1 illustrates the costs of removing trichloroethylene by the three technologies. As might be expected, the costs for all technologies decrease with increasing design capacity. At all design levels, packed-tower aeration is the cheapest technology.

A caveat on technology use

Because the source water for many utilities in the United States is groundwater, the proper conduct of bench-, pilot- and field-scale studies on technologies that effectively treat groundwater is important. The evaluation of carbon adsorption and air stripping at the field-scale level, as well as ozone oxidation, UV light, reverse osmosis, and ultrafiltration on the bench and pilot scales makes up the principal projects that have been undertaken.

Table 2 gives some guidelines as to the general performance associated with the removal of the selected set of VOCs. This table carries the caveat that the cited removals should not be used for design purposes. Each technology must be tested on compounds under field conditions before the EPA–DWRD will advocate the use of a technology.

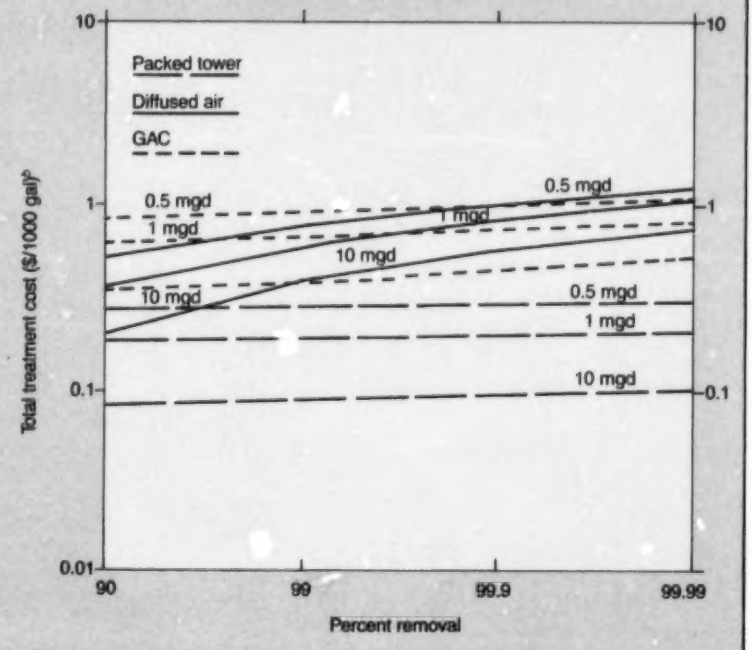
Detailed unit costs for a comparison of removal efficiencies for VOCs from groundwater using GAC and packed tower aeration have been estimated (*11*). Given the widespread nature of groundwater contamination, these technological evaluations should be highly useful to EPA's regulatory process and to consultants, state officials, and individual communities as well.

TABLE 3
Design assumptions for plant configurations

	Design Flow[a]		
	0.5 mgd	1.0 mgd	10.0 mgd
Clearwell storage—ground level, gal	500,000	100,000	1,000,000
Chlorination feed and storage, lb/day	60	120	1200
High-lift pumping head, ft	40	40	40
Cost of labor	$9.00/hr		
Cost of electricity	$0.05/kWh		
Amortization interest rate	10%		
Amortization period	20 years		
ENR construction cost index	361		

[a]mgd = million gal/day. To convert to m^3/day, multiply by 3785.
Source: Reference 11.

FIGURE 1
Cost comparison for removing trichloroethylene[a]



[a]By diffused-air and packed-tower aeration at three design flows; mgd = million gal/day.
[b]$/$m^3$ = $/1000 gal × 0.26412.

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Robert M. Clark *is director of the Drinking Water Research Division of EPA. He has been a U.S. Public Health Service officer since 1961 and is detailed to EPA. His major areas of research have been in the application of computer systems techniques and cost analysis to environmental problems.*

Carol Ann Fronk *is a research chemical engineer with the Drinking Water Research Division of EPA. After graduating from the University of Cincinnati, she began work on the removal of toxic heavy metals from wastewater and sludges. Currently, she is conducting state-of-the-art studies in the removal of VOCs and pesticides from surface water and groundwater. Her areas of expertise include membrane technology, ozone oxidation, and air stripping.*

Benjamin W. Lykins, Jr., *is chief of the systems and field evaluation branch of the Drinking Water Research Division of EPA. His major areas of research have been in removing organics from contaminated drinking water by various treatment techniques, including GAC adsorption and controlling disinfection by-products.*